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Carbon Reactivation by Externally-Fired Rotary Kiln Furnace

Los Angeles County Sanitation District, CA

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16. ABSTRACT

An externally-fired rotary kiln furnace system has been evaluated for cost-effectiveness in carbon reactivation at the Pomona Advanced Wastewater Treatment Research Facility. The pilot scale rotary kiln furnace was operated within the range of 682 kg/day (1,500 lb/day) to 909 kg/day (2,000 lb/day).

The rotary kiln furnace was found to be as effective as the multiple hearth furnace in reactivating the exhausted granular activated carbon. The operation and maintenance of the rotary kiln system required less operator skill than the multiple hearth furnace system. However, the corrosion rate was higher in the rotary tube than in the multiple hearth furnace.

Cost estimates based on a typical regeneration capacity of 182 kg/hr (400 lb/hr) have been made for both rotary kiln and multiple hearth furnace systems. These indicate that the capital cost for the multiple hearth furnace is about two times that of the rotary kiln furnace. The operation and maintenance costs for both furnace systems are similar. The overall process costs for the multiple hearth and rotary kiln furnace systems are estimated to be 33.2 cents/kg (15.1 cents/lb) of carbon regenerated and 29.2 cents/kg (13.3 cents/lb) of carbon regenerated, respectively.

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August 1980

CARBON REACTIVATION BY EXTERNALLY-FIRED ROTARY KILN FURNACE

by

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

One of the advanced treatment procedures is adsorption on activated carbon. After its capacity is exhausted the carbon is thermally regenerated. This report covers studies on regeneration in a rotary kiln furnace a lower capital cost system than that conventionally used (multiple hearth furnace).

ABSTRACT

An externally-fired rotary kiln furnace system has been evaluated for cost-effectiveness in carbon reactivation at the Pomona Advanced Wastewater Treatment Research Facility. The pilot scale rotary kiln furnace was operated within the range of 682 kg/day (1,500 lb/day) to 909 kg/day (2,000 lb/day).

The granular activated carbon used for the furnace evaluation study was exhausted in a 1.82 m (6 ft) diameter steel carbon adsorption column. The column treated the unchlorinated and unfiltered activated sludge effluent from the 0.44 cu m/sec (10 MGD) Pomona Water Reclamation Plant. The carbon adsorption column provided an empty-bed detention time of 10 minutes at a flow of 6.2 l/sec (100 gpm).

The rotary kiln furnace was found to be as effective as the multiple hearth furnace in reactivating the exhausted granular activated carbon. The operation and maintenance of the rotary kiln system required less operator skill than the multiple hearth furnace system. However, the corrosion rate was higher in the rotary tube than in the multiple hearth furnace.

Cost estimates based on a typical regeneration capacity of 182 kg/hr (400 lb/hr) have been made for both rotary kiln and multiple hearth furnace systems. These indicate that the capital cost for the multiple hearth furnace is about two times that of the rotary kiln furnace. The operation and maintenance costs for both furnace systems are similar. The overall process costs for the multiple hearth and rotary kiln furnace systems are estimated to be 33.2 cents/kg (15.1 cents/lb) of carbon regenerated and 29.2 cents/kg (13.3 cents/lb) of carbon regenerated, respectively.

This report is submitted in fulfillment of Contract No. 14-12-150 by the County Sanitation Districts of Los Angeles County under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers the entire project period from November 1975 through January 1978.

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SECTION I

INTRODUCTION

The Sanitation Districts of Los Angeles County and the United States Environmental Protection Agency have been jointly conducting an intensive pilot plant study on granular activated carbon adsorption process for wastewater treatment since 1965. The study is conducted at the Sanitation Districts' Pomona Advanced Wastewater Treatment Research Facility, Pomona, California.

The Pomona carbon study adopted a multiple hearth furnace system for carbon regeneration during the first 10 years of pilot plant operations. During this initial period, the emphasis of the study was placed on the evaluation of the various treatment process parameters, such as pretreatment requirements, carbon characteristics, adsorption capacity, backwash requirements, hydraulic loading rates, and mode of regeneration. The evaluation of different types of carbon regeneration furnace systems was not included in the initial period of study. Nevertheless, the multiple hearth furnace system was found to be very effective and very reliable in regenerating the granular activated carbon for wastewater treatment. The details of the initial carbon adsorption study results have been published elsewhere (1,2,3,4).

It is essential that every important aspect of any treatment process scheme should be thoroughly studied before the process can be considered to be fully investigated. Carbon regeneration is a major factor in the determination of the carbon process feasibility and cost effectiveness for wastewater treatment. Although economical regeneration had been achieved with the multiple hearth furnace, it was considered to be capital intensive compared to a rotary kiln furnace. Therefore, the study presented in this report was initiated to determine if an externally-fired rotary kiln could be successfully utilized for regeneration of granular activated carbon.

Filtrasorb 300 granular activated carbon was exhausted by exposure to secondary effluent in a downflow carbon contactor and then regenerated in the rotary kiln. This process was repeated for several cycles. The performance of the carbon after regeneration was evaluated by its adsorption effectiveness in the next adsorption cycle. The performance of the rotary kiln furnace was compared to that of a multiple hearth furnace which had regenerated the same type of carbon from this same type of pilot carbon contactor exhausted with the same activated sludge plant effluent.

The comparison was based on the ability to regenerate the carbon, fuel and power consumption, ease of control and operation, and extent of carbon losses. The studies with the multiple hearth furnace were not in parallel with those on the rotary kiln but were done at an earlier time. The comparison study was initiated in November 1975, and completed in January 1978. This report was prepared in May 1979.

SECTION II

CONCLUSIONS

The following conclusions can be drawn from the pilot plant study:

A. The externally-fired rotary kiln furnace system was effective as the multiple hearth furnace system in reactivating granular activated carbons which were exhausted by an activated sludge plant effluent.

B. The rotary kiln regeneration system required less operational skill and maintenance labor than the multiple hearth furnace system.

C. The usable life span of the rotary kiln was rather short compared to the life of the multiple hearth furnace.

D. The fuel consumption rate averaged 27,520 kJ/kg (11,830 BTU/lb) for the externally-fired rotary kiln pilot plant. This consumption rate was about twice that of a multiple hearth system.

E. Both rotary kiln and multiple hearth furnace systems required an afterburner and a venturi wet scrubber for effective control of emissions of air pollutants.

F. The average carbon loss observed in the operation of the rotary kiln pilot plant was approximately 7 percent per regeneration cycle. This is equivalent to the carbon loss of a multiple hearth furnace system.

G. The total process cost for a 182 kg/hr (400 lb/hr) externally-fired rotary kiln system is estimated to be about 29.2 cents/kg (13.3 cents/lb) of carbon compared to 33.2 cents/kg (15.1 cents/lb) of carbon for a multiple hearth system with an equivalent regeneration capacity.

SECTION III

RECOMMENDATIONS

A. A comparison study of an externally-fired rotary kiln system and an internally-fired rotary kiln system should be conducted.

B. The life of a rotary kiln under steady operating conditions should be determined.

C. Evaluation of a more energy saving rotary kiln provided with furnace flights, better furnace insulation and heat recovery system should be performed.

D. Optimization of the air pollution control system for rotary kiln furnace should be conducted.

E. Other carbon regeneration systems, such as Shirco infrared moving belt system and Westvaco moving bed system, should be investigated to provide sufficient information for making furnace system selection.

SECTION IV

PILOT PLANT DESCRIPTION

A general layout of the 6.2 l/sec (100 gpm) pilot plant system is shown in Figure 1. Basically, the pilot plant consisted of a carbon contacting column, a carbon dewatering and regeneration system, and an air pollution control system.

CARBON CONTACTING COLUMN

The carbon contacting column used to provide the exhausted carbon for the regeneration study is shown in Figure 2. The column was a steel column with 1.83 m (6 ft) in diameter and 4.88 m (16 ft) in height. The column was operated in a downflow gravity mode. As indicated in the figure, the carbon bed was supported by a Neva Clog stainless steel screen. A surface wash piping system was provided at about 5 cm (2 in) above the surface of the unexpanded carbon bed in the column. The interior surface of the steel column was coated with corrosion-inhibiting bitumastic coal-tar epoxy. The column contained about 1,590 kg (3,500 lbs) of Calgon Filtrasorb 300 (8 x 30 mesh) granular activated carbon. Table 1 presents the typical characteristics of the carbon. The depth of the carbon bed in the column was approximately 1.37 m (57 in) providing an empty-bed contact time of 10 minutes at a system flow of 6.3 l/sec (100 gpm).

CARBON REGENERATION SYSTEM

The rotary kiln carbon regeneration furnace system was manufactured by the former T. M. Melsheimer Co., Compton, California. The furnace system contained two externally-fired rotary kilns with identical design. The kilns were made of Type 309 stainless steel with dimensions of 38.1 cm (15 in) in diameter and 4.27 m (14 ft) in length. The rotary kilns were driven by an 1/3 hp (0.25 kW) drive mechanism and had a common slope of 0.008 toward exit ends. The furnace was designed for an operating temperature range of 790°C (1,450°F) to 960°C (1,760°F). The rotary kiln furnace system had a rated total regeneration capacity range of 682 kg (1,500 lbs) to 909 kg (2,000 lbs) of granular activated carbon per 24 hour period.

The spent carbon was first dewatered in a 61 cm wide by 122 cm long by 122 cm deep (2 ft X 4 ft X 4 ft) wood chamber. The partially dewatered, spent carbon was then manually shovelled into the stainless steel feed hoppers. Each feed hopper had a nominal capacity of 230 kg (500 lbs) carbon. Each feed hopper was equipped with an 1/4 hp (0.19 kW) vibrator and a variable speed screw conveyor to facilitate the control of the carbon feed rate to each rotary kiln.

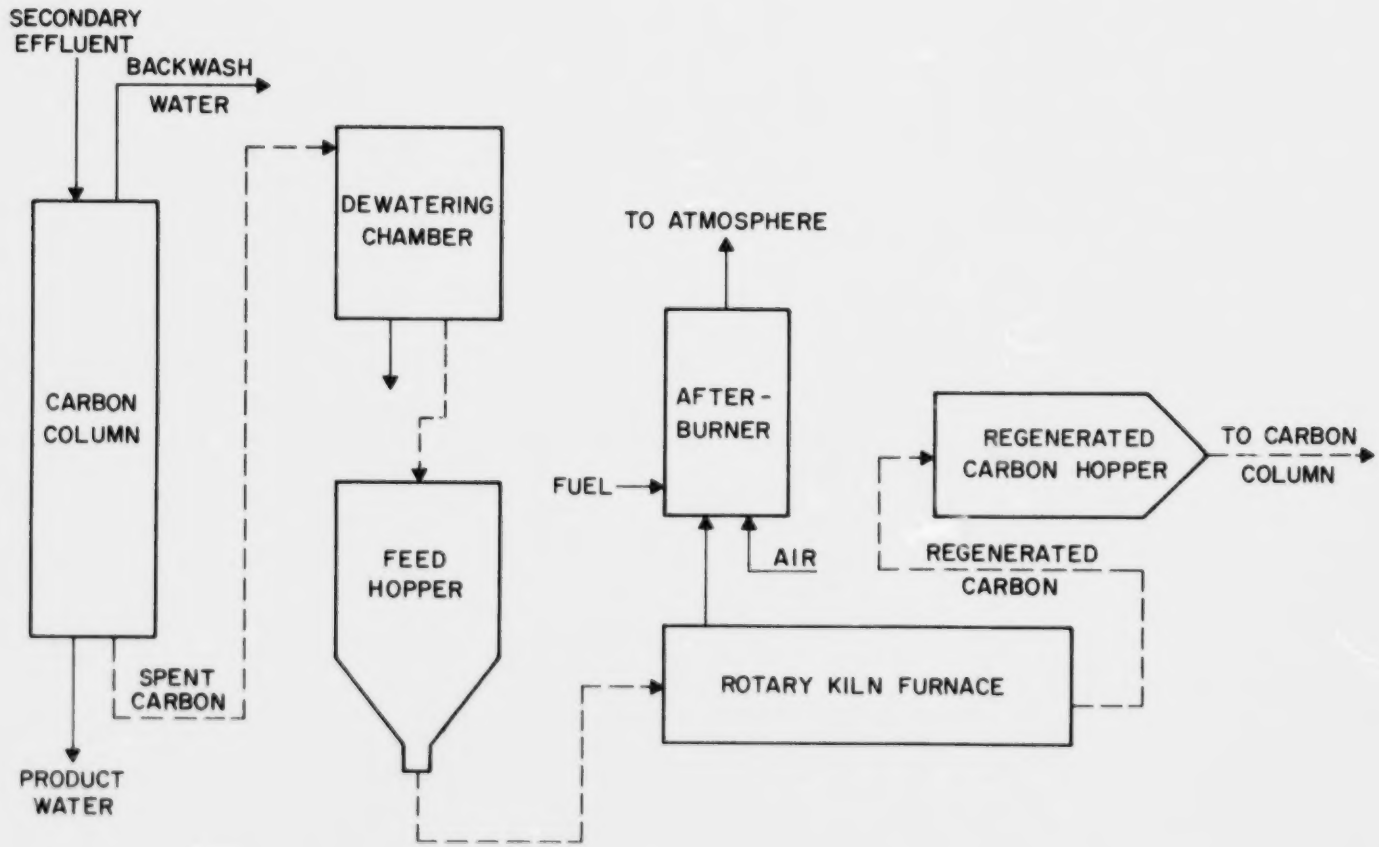


Figure 1. Schematic diagram of rotary kiln carbon regeneration system.

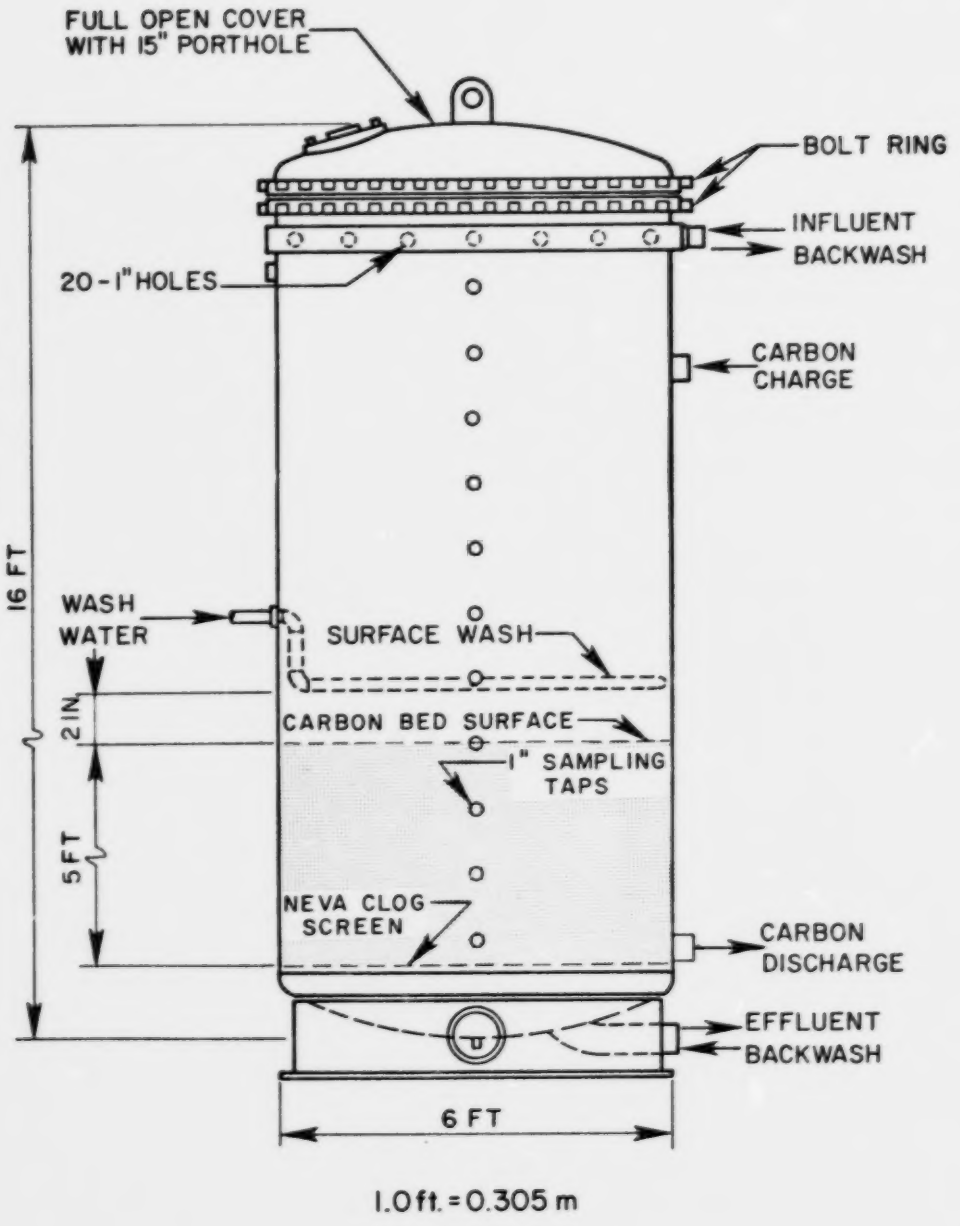


Figure 2. Carbon adsorption column.

TABLE 1

CHARACTERISTICS OF FILTRASORB 300 GRANULAR ACTIVATED CARBON

Molasses Number		210
Iodine Number, mg/g		1040
Apparent Density, g/cc		0.484
Methylene Blue Number, mg/g		256
Ash, %		6.4
Mean Particle Diameter, mm		1.44
Sieve Analysis:		
% retained on U.S. Sieve No.,	8	3.5
	10	12.6
	12	19.2
	14	16.3
	16	15.1
	18	9.0
	20	6.8
	30	11.7
	pan	5.8

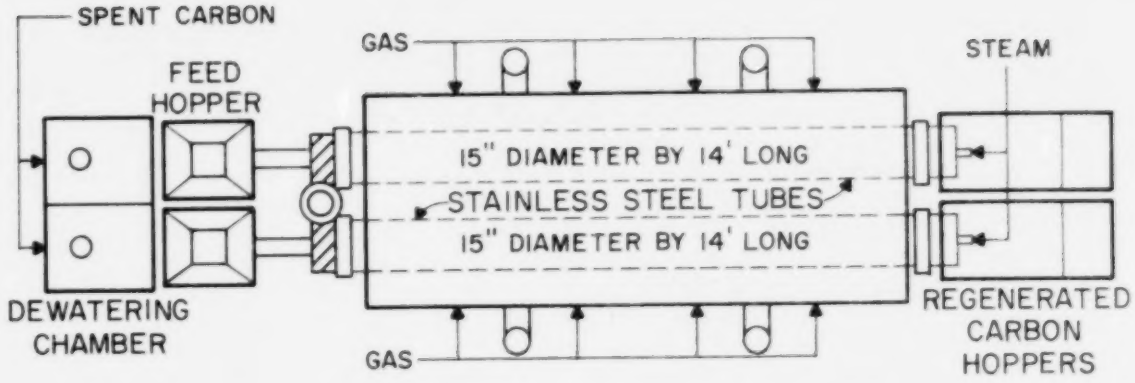
As indicated in Figure 3, a total of eight atmospheric gas burners were provided along both sides of the furnace. KAO wool and K-20 fire brick were used to insulate the furnace system. The KAO wood blanket (in two layers) covered the entire sides and roof of the furnace interior. Mineral wool block was set between the KAO wool blanket and the shell of the furnace for further insulation. The insulation was designed to keep the shell below 100°C (212°F) at normal interior operation temperatures. The shell was made of low carbon steel sheet to provide protection and support.

Six sets of thermocouples were provided along the length of each rotary kiln for monitoring the furnace temperature profile. The thermocouples were located at 0.61 m (2 ft) intervals starting at 0.61 m (2 ft) from the carbon feed end. The third set of thermocouple at 1.83 m (6 ft) from the carbon feed end was used as a temperature indicator-controller for controlling the furnace operating temperature at desired level. The thermocouples were located about 2.54 cm (1 in) above the rotary kilns. The desired amount of steam was introduced at the exit end of each rotary kiln with a flow measurement and control device.

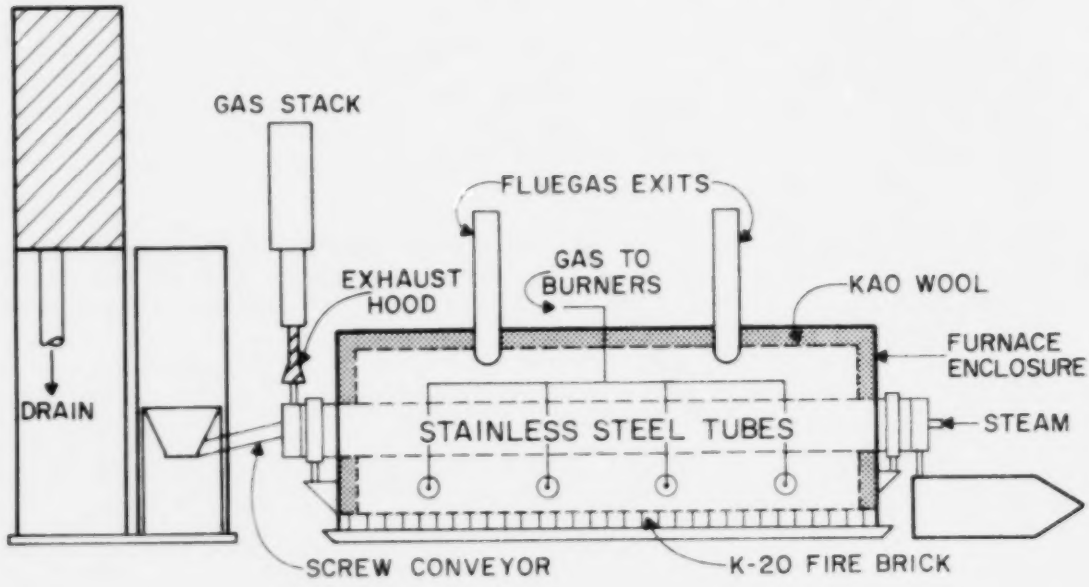
AIR POLLUTION CONTROL SYSTEM

The rotary kiln furnace pilot system was only equipped with an afterburner unit for its air pollution control. This was based on the manufacturer's claim that such a simple air pollution control system performed satisfactorily in a similar application(5). Two eclipse single stage, low pressure atmosphere injecting gas burners (Model TR-6 injector with Eclipse ST-206 nozzle) were mounted right above the exits of the exhaust from the two rotary kilns. Each of the gas burners had a rated capacity of 58,000 kJ/hr (55,000 BTU/hr).

During the carbon regeneration, the furnace exhaust was burned together with air by the open-air gas burners. The burned air-exhaust mixture was dispersed through a stainless steel stack at a height of approximately 6.1 m (20 ft) from the ground level.



PLAN
1' = 12" = 0.305 m



ELEVATION
1' = 12" = 0.305 m

Figure 3. Rotary kiln regeneration system.

SECTION V

PILOT PLANT OPERATION

OPERATION OF CARBON CONTACTING COLUMN

Carbon Adsorption

During the carbon regeneration comparison study, the unchlorinated and unfiltered secondary effluent from the Pomona Water Reclamation Plant was treated directly by the carbon adsorption systems. The Pomona Water Reclamation Plant is a 0.44 cu m/sec (10 MGD) activated sludge plant. The typical water quality produced by the plant is shown in Table 2.

A 15.2 cm (6 in) diameter steel pipe was used to transfer the unchlorinated secondary effluent from the Pomona Water Reclamation Plant to the Pomona Advanced Wastewater Treatment Research Facility at a maximum total flow rate of 37.9 l/sec (600 gpm). A surge tank at the research site was used to hold the secondary effluent for supplying the pilot plant study by an influent pumping system. The product water from the carbon column and the excess water from the surge tank were discharged together to the creek after adequate chlorination.

The contacting carbon column was operated in a gravity downflow mode at a constant rate of 6.3 l/sec (100 gpm) thereby providing a hydraulic loading rate of 2.4 l/sec/sq m (3.5 gpm/sq ft) and an empty-bed contact time of approximately 10 minutes. As indicated in Figure 2, the column feed water entered the top of the contactor through an annular distribution ring containing twenty 2.54 cm (1 in) diameter holes around the circumference of the contactor. The entrance annular ring was located about 2.5 m (8.3 ft) above the top of the carbon bed, thus providing sufficient space for bed expansion during backwashing.

Backwash of Carbon Bed

The carbon bed was backwashed daily to maintain good hydraulic conditions for operation. The carbon column was usually taken off stream for backwash at 8:00 A.M., and it was back on stream at approximately 9:00 A.M.

The unchlorinated secondary effluent from the Pomona Water Reclamation Plant was used as wash water for the carbon bed backwash operation. The backwash schedule, as indicated in Figure 4, consisted of a surface wash at a constant rate of 1.22 l/sec/sq m (1.8 gpm/sq ft) for 10 minutes and a stepwise water backwash to a maximum rate of 7.13 l/sec/sq m (10.5 gpm/sq ft) within a total

TABLE 2

SUMMARY OF POMONA WATER RECLAMATION PLANT SECONDARY EFFLUENT WATER QUALITY CHARACTRERISTICS (JANUARY 1 to DECEMBER 31, 1977)

Parameter	Range	Mean
Total Cadmium, µg/l	1 - 6	2.8
Total Chromium, mg/l	0.01 - 0.02	0.01
Total Copper, mg/l	0.005 - 0.020	0.015
Total Iron, mg/l	0.02 - 0.14	0.05
Total Lead, mg/l	0.01 - 0.04	0.02
Total Nickel, mg/l	0.02 - 0.08	0.04
Potassium, mg/l	10 - 16	11.8
Total Silver, µg/l	1 - 3	1.4
Sodium, mg/l	94 - 121	111
Total Zinc, mg/l	0.042 - 0.160	0.081
Total Hardness, mg/l $CaCO_3$	185 - 207	200
Total Alkalinity, mg/l $CaCO_3$	127 - 252	207
Total Dissolved Solids, mg/l	479 - 667	567
Chloride, mg/l Cl	92 - 119	104
Sulfate, mg/l SO_4	93 - 119	111
Nitrate, mg/l N	0.01 - 20.5	2.81
Nitrite, mg/l N	0.01 - 3.65	1.11
Ammonia, mg/l N	0.07 - 19.6	11.7
Organic Nitrogen, mg/l N	0.6 - 2.1	1.1
Phosphate, mg/l PO_4	17.0 - 25.2	21.6

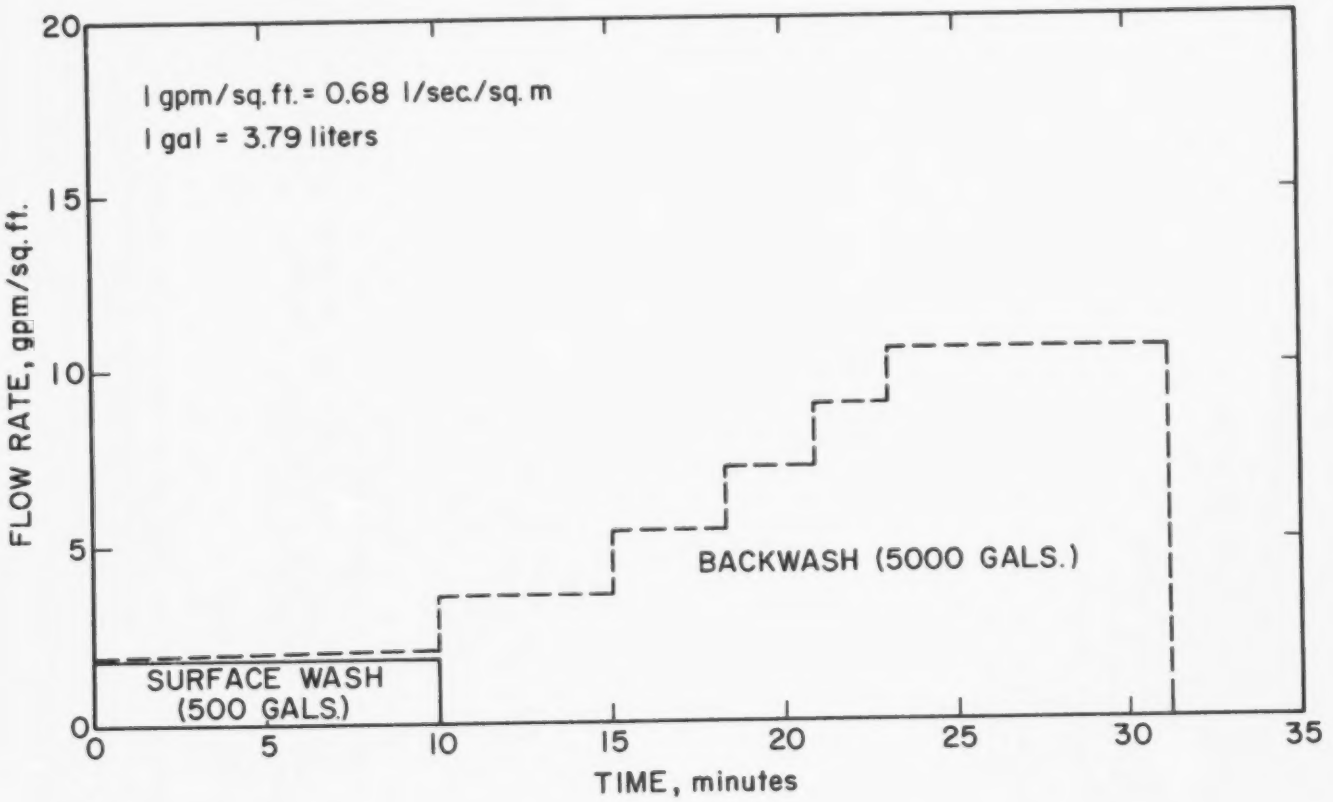


Figure 4. Carbon adsorption column backwash schedule.

period of approximately 32 minutes. The total volumes of water used for surface wash and backwash were equal to 1.89 cu m (500 gallons) and 18.9 cu m (5,000 gallons), respectively. The combined total of water consumed in backwash was about 4 percent of the total volume of product water.

During backwashing, the backwash water was discharged into a holding tank designed to capture any accidental carbon spills and to allow visual observation of the clarity of the backwash water. The backwash water containing heavy accumulations of biological flocs and some carbon fines overflowed a weir in the holding tank and was pumped into the head end of the primary sedimentation tanks of the Pomona Water Reclamation Plant.

While adequate space was provided above the carbon bed in the contacting column for bed expansion during backwash cycle, routine column backwash operation was limited to a maximum upflow rate of 7.3 l/sec/sq m (10.5 gpm/sq ft) because of the limitation on the structural strength of the underdrain screen. At the backwash rate of 7.13 l/sec/sq m (10.5 gpm/sq ft), the measured bed expansion was about 10 percent.

The headloss buildup through a granular activated carbon column operated on a packed-bed and downflow mode, was found to be influenced by such factors as hydraulic surface loading, influent suspended solids level, carbon particle size and the length of filter run. The average total headloss buildup through the carbon bed was about 0.17 kg/sq cm (2.5 psig) for a 23 hour operation period during the study.

Carbon Transfer for Regeneration

Normally, the carbon contacting column treated a total volume of 22,710 cu m (6 million gallons) of Pomona Water Reclamation Plant secondary effluent before it was taken off stream in preparation for carbon regeneration. The COD removal efficiency of the carbon column usually reached a leveling off value at this cut off volume.

The spent carbon was thoroughly backwashed before being hydraulically transferred as a slurry to the elevated dewatering chamber. The backwash procedure was similar to that used for routine column backwash except for the fact that the last backwash step was prolonged to provide a total backwash water volume of about 79.5 cu m (21,000 gallons).

CARBON REGENERATION

The dewatered spent carbon, with about 50 percent moisture content, was transferred from the feed hoppers through screw conveyors into two parallel rotary kiln furnaces. The carbon feed rate to each rotary kiln was maintained at approximately 16 kg/hr (35 lb/hr). The average steam consumption rate was 0.3 kg steam/kg carbon. The kilns were rotated automatically at an average rate of 6 revolutions per minute.

The regeneration temperature was maintained at 885°C (1,625°F) by the temperature indicator-controller which was located 1.83 m (6 ft) from the

carbon feed end. The feed end was usually about 93°C (200°F) lower than the controlling temperature. The regenerated carbon was discharged from the rotary kilns into two covered storage hoppers for carbon cooling. The cooled carbon was periodically shovelled into 208 l (55 gallon) drums which were then emptied into the carbon contactor through a hoist system.

CARBON MAKE-UP

After carbon regeneration, the regenerated carbon was put back in the contactor and thoroughly backwashed with 57 to 76 cu m (15,000 to 20,000 gallons) of secondary effluent to remove carbon fines. Appropriate amount of make-up carbon was then added to replace the carbon lost during regeneration. The contactor, with the added make-up virgin carbon, was backwashed again with 7.6 to 19 cu m (2,000 to 5,000 gallons) of secondary effluent before the contactor was placed back in operation.

SAMPLING AND TESTING

During the carbon adsorption and regeneration cycles, appropriate samples were taken for evaluating the carbon adsorption and carbon reactivation efficiencies. The types, locations, and frequencies of the various samples taken during the study are described as follows.

Water Quality Monitoring

Refrigerated 23 hour composite samples (9:00 A.M. to 8:00 A.M. next day) of influent and effluent from the carbon contacting column were collected automatically using timer-controlled solenoid valves. These samples were analyzed daily for turbidity and three times a week for total chemical oxygen demand (TCOD), dissolved chemical oxygen demand (DCOD), suspended solids (SS) and color. Determinations for pH and temperature were performed on grab samples three times a week. All analyses were performed in accordance with the Standard Methods(6).

Carbon Regeneration Control Test

In the course of carbon regeneration, a number of control tests, consisting of the determinations of apparent density, iodine number, methylene blue number, and molasses number, were performed to regulate the regeneration process and monitor the quality of the regenerated carbon. All tests were performed using standardized procedures of the Pittsburgh Activated Carbon Company(7).

The test for apparent density was determined routinely every hour whereas the tests for iodine and molasses numbers were performed every four hours and two hours, respectively. The six to eight grab samples of spent carbon, collected during carbon transfer, and the hourly samples of regenerated carbon were composited over the regeneration period. These composited carbon samples were analyzed for apparent density, molasses number, iodine number, methylene blue number, ash content, and mean particle size.

SECTION VI

PILOT PLANT RESULTS AND DISCUSSIONS

PERFORMANCE OF CARBON CONTACTING COLUMN

Four adsorption cycles were performed with the carbon contacting column during the entire rotary kiln regeneration study period. The average values of water quality parameters for each adsorption cycle are presented in Table 3. The overall averages for the entire operation are also included in the table.

As indicated in Table 3, the average volume of secondary effluent processed through the carbon contacting column during each adsorption cycle was about 24,200 cu m (6.4 million gallons). The average pressure drop before the daily backwash of the carbon column was approximately 0.18 kg/sq cm (2.5 psig). The carbon column with a carbon-bed depth of 1.37 m (57 in) seemed to be generally effective for suspended solids and turbidity removals. These removals averaged 83.6 percent and 72.9 percent for the suspended solids and turbidity, respectively.

The removals of color and dissolved chemical oxygen demand (DCOD) by the carbon column are illustrated in Figures 5 and 6, respectively. Both color and DCOD were effectively removed by the carbon in the early portion of each adsorption cycle. As the carbon approached exhaustion, both color and DCOD removals seemed to level off at approximately 40 percent and 30 percent, respectively. These phenomena may be attributed to the biological reactions taking place inside the carbon bed. The total average removals for color and DCOD over an adsorption cycle were 54.8 percent and 42.9 percent, respectively. The color removal seemed to improve slightly after each carbon regeneration. This phenomenon was accompanied by a similar trend of molasses number increase with the number of the carbon regeneration, which is indicated in Table 4 and Figure 7.

A comparison of DCOD adsorption capacities with respect to adsorption cycles is presented in Figure 8. As indicated in the figure, the DCOD adsorption capacity curve for each adsorption cycle follows very closely to each other, especially at low levels of applied DCOD. This similarity adequately demonstrates that the rotary kiln regeneration system could consistently restore the operational carbon adsorption capacity in its repeated regeneration cycles.

TABLE 3

SUMMARY OF CARBON ADSORPTION COLUMN PERFORMANCE DURING ROTARY KILN REGENERATION STUDY

Parameter	Adsorption Cycle First	Second	Third	Fourth
Total Flow Processed, MG	4.81	6.83	6.76	7.1[illegible]
Daily Pressure Drop, psig	--	1.9	2.7	2.[illegible]
Suspended Solids, mg/l				
Column Influent	12.6	9.0	12.9	10.[illegible]
Column Effluent	2.8	2.0	1.8	1.[illegible]
Turbidity, FTU				
Column Influent	5.1	3.7	6.0	4.[illegible]
Column Effluent	1.5	1.4	1.5	1.[illegible]
Color, color unit				
Column Influent	31	33	31	3[illegible]
Column Effluent	15	15	13	1[illegible]
Total COD, mg/l				
Column Influent	39.6	42.4	45.1	40.[illegible]
Column Effluent	17.9	20.8	20.4	17.[illegible]
Dissolved COD, mg/l				
Column Influent	25.3	32.2	28.1	25.[illegible]
Column Effluent	14.3	18.6	16.2	14.[illegible]
pH				
Column Influent	7.3	7.7	7.5	7.[illegible]
Column Effluent	7.3	7.7	7.6	7.[illegible]
Temperature, °C				
Column Influent	22.9	24.5	22.0	27.[illegible]
Column Effluent	22.9	24.7	21.7	26.[illegible]
Operation Period				
On	10/29/75	9/22/76	1/25/77	5/19/77
Off	12/31/75	1/ 6/77	4/22/77	8/24/77

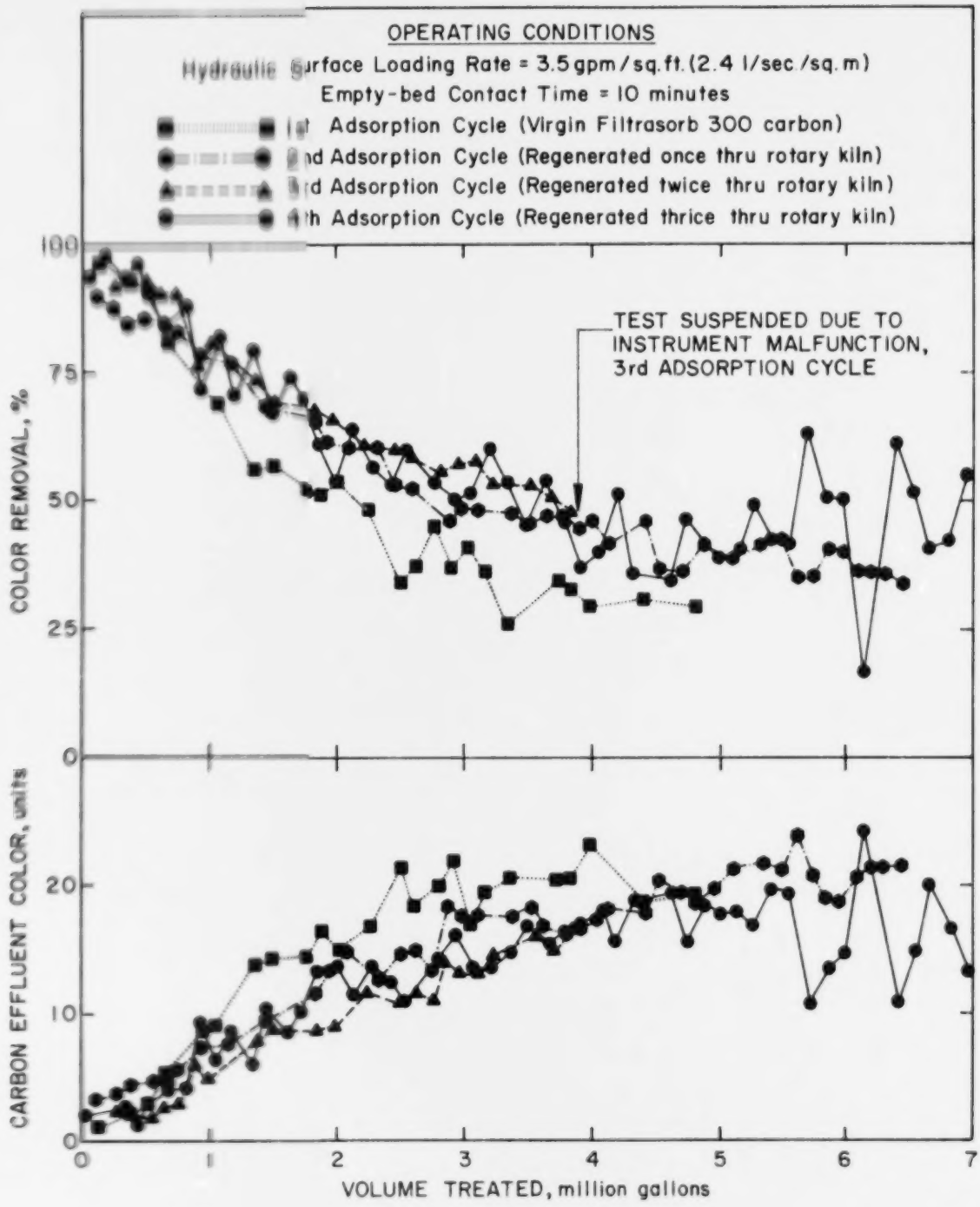


Figure 5. Color removal through the carbon column.

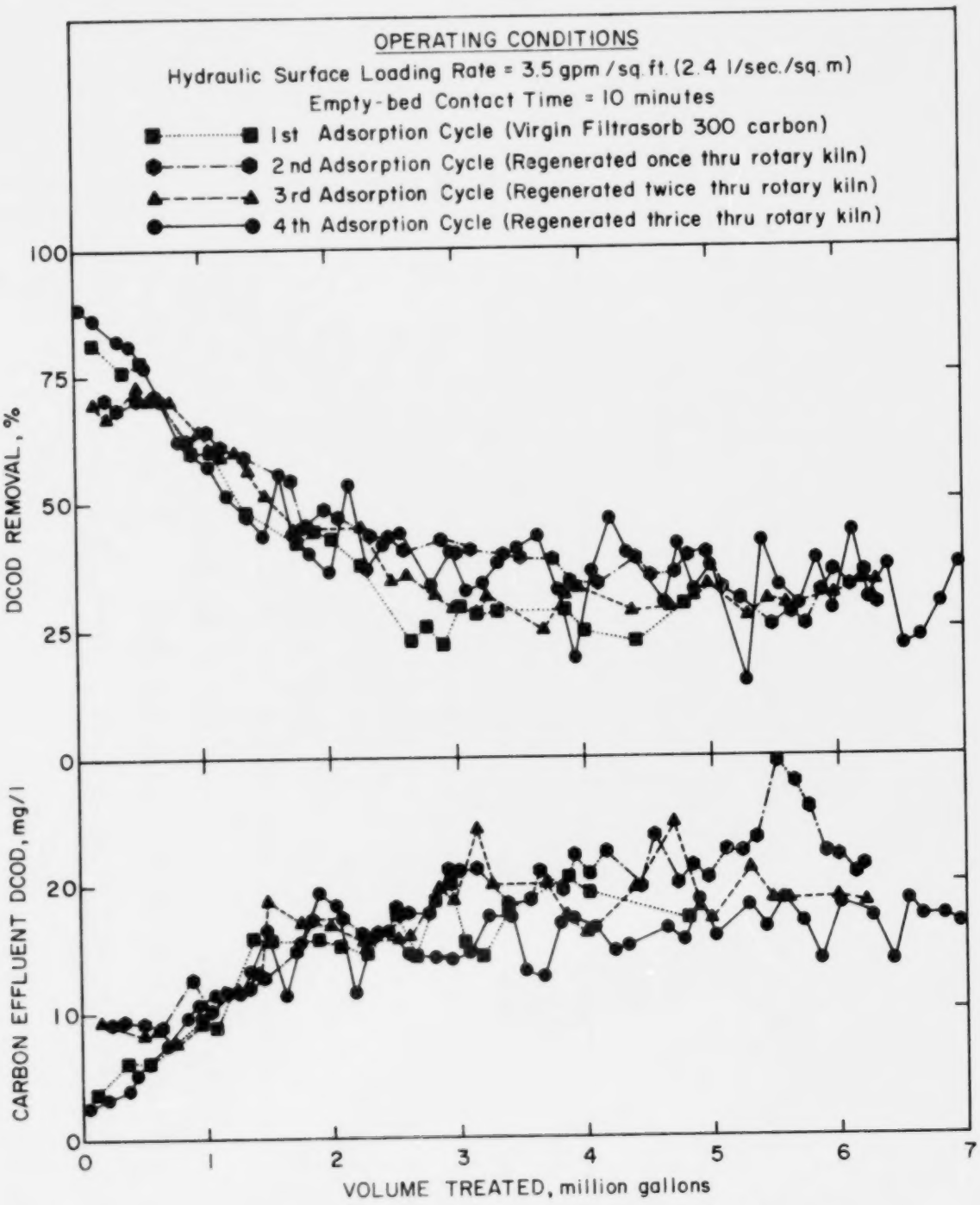


Figure 6. Dissolved COD removal through the carbon column.

TABLE 4

RESULTS OF CARBON CONTROL TESTS DURING ROTARY KILN REGENERATION STUDY

Parameter	First Regeneration		Second Regeneration		Third Regeneration		Fourth Regeneration	
	S	R	S	R	S	R	S	R
AD, g/cc	0.522	0.519	0.564	0.502	0.559	0.514	0.548	0.517
IN, mg/g	623	886	610	846	620	831	616	773
MN	155	210	142	220	206	241	186	241
MBN, mg/g	241	260	169	258	158	251	163	252
Ash, %	6.5	7.3	7.2	8.4	7.4	8.2	-	9.7
MPD, mm	1.66	1.50	1.58	1.46	1.48	1.46	1.61	1.46

NOTES: 1. The data were based on the composite samples of both rotary kilns.

2. S = spent carbon; R = regenerated carbon

3. AD = Apparent density; IN = Iodine number; MN = Molasses number; MBN = Methylene blue number; MPD = Mean particle diameter.

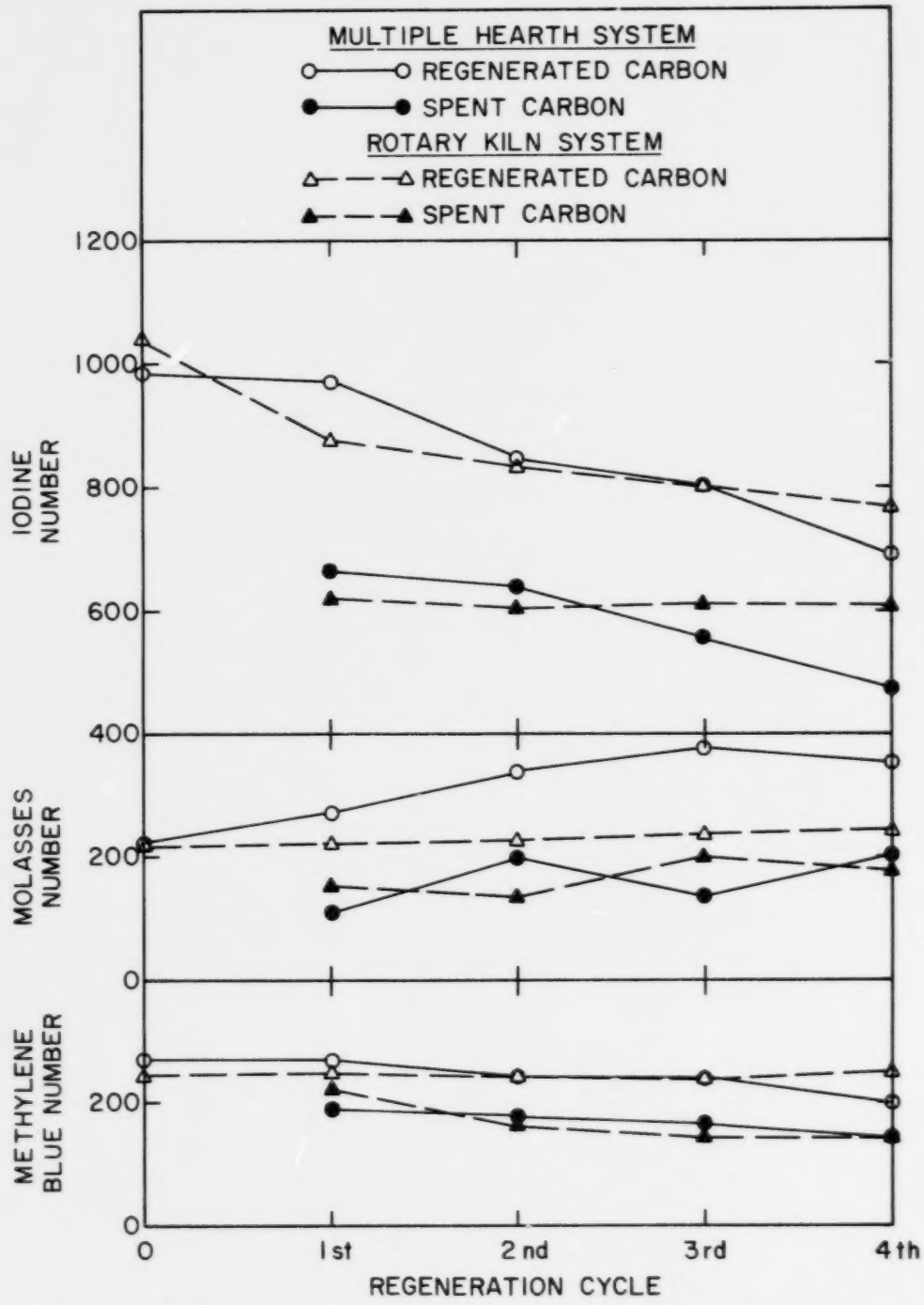


Figure 7. Effect of carbon regeneration on iodine, molasses, and methylene blue numbers.

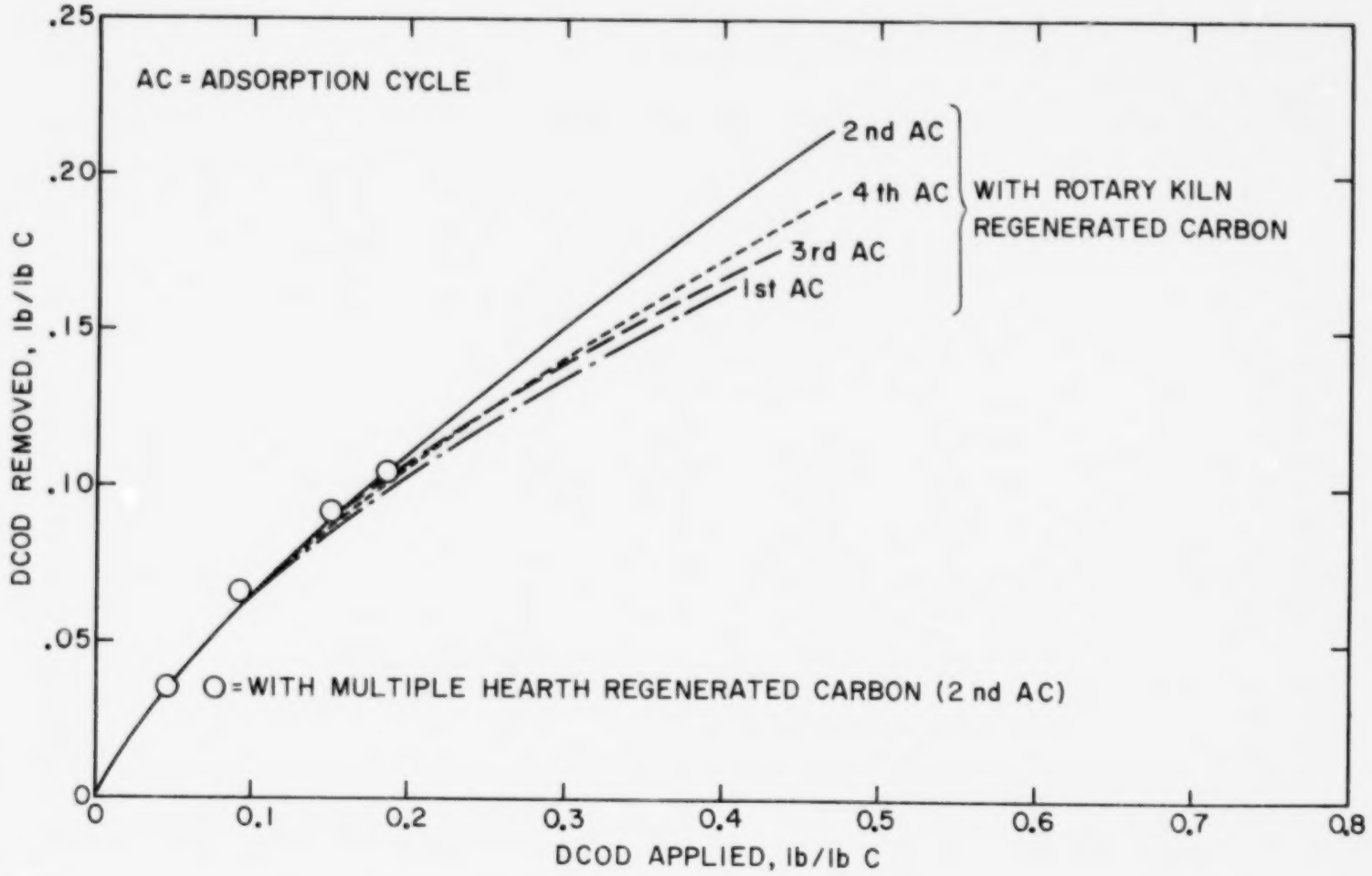


Figure 8. DCOD adsorption capacity comparison among various adsorption cycles.

PERFORMANCE OF REGENERATION SYSTEM

During initial operation of the rotary kiln carbon regeneration system, some mechanical difficulties were encountered. The problems were generally in the areas of carbon dewatering, carbon feed, gas burner, steam monitoring, and furnace temperature control. Most of these problems were associated with improper designs in the original system. Several system modifications were per formed before the layout as shown in Figure 3 was accomplished for routine operation. This system modification had caused a long shut-down time between the first and second adsorption cycles, which is indicated in Table 3.

Furnace Operating Temperature

Usually it required about 90 minutes for the rotary kiln system to reach the desired furnace operating temperature. The actual feeding of the spent carbon into the kilns was initiated 30 minutes after the preset controlling temperature was reached.

The average operating temperatures at various thermocouple locations along the length of the rotary kiln system for each regeneration cycle are shown in Table 5. As indicated in the table, the average temperature at the carbon feed end of the rotary kiln was about 93°C (200°F) lower than the temperature at the location of temperature indicator-controller, which was located about half-way of the length of the rotary kiln. The average temperature along the rotary kiln in the last 3.05 m (10 ft) section ranged from 891°C (1,635°F) to 916°C (1,681°F). This relatively small variation seemed to indicate a rather uniform temperature distribution along the last 3.05 m (10 ft) section of the rotary kiln system. The regeneration temperature range of 891°C (1,635°F) to 916°C (1,681°F) in the rotary kiln system is slightly lower than the range of 916°C (1,681°F) to 932°C (1,710°F) observed in the multiple hearth furnace system[3].

The temperature at the temperature indicator-controller was gradually decreased from an average of 936°C (1,716°F) in the second regeneration cycle to 893°C (1,640°F) and 876°C (1,608°F) for the third and fourth regeneration cycles, respectively. The purpose of this procedure was to determine the lower limit of furnace operating temperature which would be equally effective for carbon regeneration.

Carbon Feed Rate

Table 6 summarizes the rotary kiln operating conditions for the four carbon regeneration cycles. As indicated in the table, the average carbon feed rate for each rotary kiln ranged form 14.7 kg/hr (32.3 lb/hr) to 19.0 kg/hr (41.7 lb/hr), with an overall average of 16.0 kg/hr (35.1 lb/hr). The highest carbon feed rate occurred in the first regeneration cycle which was considered as a shake down operation of the rotary kiln regeneration system. The average travel time of carbon through the rotary kiln was estimated to be 30 minutes with the kiln rotated at an average rate of 6 revolutions per minute.

TABLE 5

SUMMARY OF ROTARY KILN FURNACE OPERATING TEMPERATURES (°F)

Thermocouple Number	Distance From Feed End, ft	Regeneration Cycle				Overall Average
		First	Second	Third	Fourth	
1	2	--	1509	1413	1392	1461
2	4	--	1670	1599	1543	1635
3	6	1681	1716	1640	1608	1661
4	8	--	1755	1651	1637	1681
5	10	--	1741	1627	1622	1663
6	12	--	1720	1586	1592	1633

NOTES: 1. All temperature data were based on the average of two rotary kilns.

2. Thermocouple Number 3 was used as the temperature indicator-controller.

3. $(°F - 32) \times \frac{5}{9} = °C$; ft X 0.305 = m

TABLE 6

SUMMARY OF ROTARY KILN FURNACE OPERATING CONDITIONS

Parameter	Regeneration Cycle				
	First	Second	Third	Fourth	Overall Average
Total Carbon Regenerated, lb	3,420	3,420	3,010	3,370	3,305
Duration of Regeneration, hr	41.0	53.0	45.0	51.5	47.6
Carbon Feed Rate, lb/hr	83.4	64.5	66.9	65.4	70.1
Steam Used, lb/lb carbon	0.24	0.31	0.30	0.30	0.29
Total Fuel Used, BTU/lb carbon	9,070	13,050	12,370	12,820	11,830
Carbon Loss, %	12.9	6.3	6.0	7.6	6.6

NOTE: 1. Approximately 400 lbs of carbon were lost to drain during carbon transfer for third carbon regeneration cycle.

2. Substantial carbon loss was caused by on-and-off shake-down operations during the first carbon regeneration cycle. Consequently, the unusually high 12.9% carbon loss was not used in the calculation of the overall carbon loss average.

3. The carbon feed rates were based on the sums of two rotary kiln.

Steam and Fuel Consumption Rates

During the regeneration cycle, the steam was continuously injected at the exit ends of the rotary kilns at the rate of 4.5 kg/hr (10 lb/hr) for each of the two rotary kilns. Because of this constant injection rate, the calculated steam consumption rate thus varied from 0.24 to 0.31 kilogram of steam per kilogram of carbon, depending on the variations of the carbon feed rate. This steam consumption rate range was about one-half of the steam consumption rate used in the multiple hearth furnace operations having an average carbon feed rate of 37.1 kg/hr (81.7 lb/hr).

As indicated in Table 6, the total fuel consumption rate for the first regeneration cycle was about 21,000 kJ/kg carbon (9,070 BTU/lb carbon), which was about 23 percent lower than the overall average fuel consumption rate. Since the heat energy required to maintain the furnace operating temperature is practically constant and is only slightly affected by the moderate variation of carbon feed rate, the calculated fuel consumption rate on unit carbon weight will be affected inversely by the carbon feed rate. Therefore, the lower fuel consumption rate in the first regeneration cycle might be caused by the relatively higher carbon feed rate in the first regneration cycle, which was about 19 percent higher than the average carbon feed rate for the entire study.

The operation of the rotary kiln system during the initial eight hours, which represented about 20 percent of the total regeneration time used in the first regeneration cycle, was on an on-and-off basis due to various mechanical difficulties. This unusual mode of operation resulted in a heavy carbon loss of 12.9 percent as indicated in Table 6.

The carbon losses in the subsequent three regeneration cycles were about 6.3, 6.0, and 6.6 percent. These levels of carbon losses were very similar to the results obtained from the multiple hearth furnace operation[3].

As indicated in Table 6, about 181 kg (400 lbs) of carbon were inadvertently lost through an open drain valve during the preparation of carbon transfer for the third regeneration cycle. This type of carbon loss was not included in the carbon loss calculation.

Carbon Adsorption Capacity

In the course of thermal regeneration, the organic pollutants on the surfaces of the external and pore areas of carbon are oxidized and removed. However, this oxidation process does not completely remove the adsorbed organics from the carbon pores. Therefore, a certain amount of theoretical adsorption capacity is normally lost in every thermal regeneration cycle. In addition to this cause for capacity loss, the change of pore size distribution in the regeneration process may also contribute to the reduction of theoretical carbon adsorption capacity. The carbon adsorption capacity recovery can be monitored by the determinations of the iodine number, molasses number, and methylene blue number on both spent and regenerated carbons. Table 4 summarizes the values of the carbon characteristic numbers obtained in the rotary kiln regeneration study.

As indicated in Tables 1 and 4, the iodine number of the virgin Calgon Filtrasorb 300 granular activated carbon was about 1,040 mg/g, and it was reduced to 623 mg/g, a 40 percent reduction, at the end of the first adsorption cycle. This reduction in iodine number was partially recovered from 623 mg/g to 886 mg/g in the first regeneration cycle by the rotary kiln system. A continuing decrease in the iodine number with respect to regeneration cycle is apparent from Figure 7, although the cyclic thermal regeneration was effective in restoring the operational adsorption capacity, as shown in Figure 8.

On the contrary, the molasses number was found to be gradually increased with the number of regeneration cycle. Since the molasses number related to the surface area of the pores with a diameter larger than 28 angstroms, the increase in molasses number indicated an enlargement of micropore structures to macropore structures in the carbon during the repeated thermal regeneration process. This shift in pore size distribution also caused a reduction of total surface area of the carbon, which was indicated by the reduction of the iodine number. The molasses number of the virgin carbon was about 210, and it was increased to 241, a 15 percent increase, at the end of the fourth regeneration cycle. This increase in molasses number seemed to improve the color removal slightly as shown in Table 3 and Figure 5.

Another parameter used to measure pore enlargement during thermal regeneration was the methylene blue number. This number related to surface area of carbon pores with diameter larger than 15 angstroms. As indicated in Tables 1 and 4, the methylene blue number of the carbon after four regeneration cycles was about 252 mg/g as compared to 256 mg/g of the virgin carbon.

The ash content of the regenerated carbon, which measured the buildup of inorganic residues, increased significantly from a level of 6.4 percent for the virgin carbon to 9.7 percent for the carbon with four thermal regeneration cycles. The mean particle diameter seemed to maintain at a fairly constant level of 1.46 mm in all four regeneration cycles. Similarly, the apparent density of the regenerated carbon only fluctuated slightly between 0.502 and 0.519 g/cu cm, as indicated in Table 4.

The effects of the rotary kiln carbon regeneration on the various carbon characteristic numbers, as discussed in the above paragraphs, are very similar to those observed in the multiple hearth carbon regeneration study[3]. These similarities are illustrated in Figure 7. Apparently, both rotary kiln and multiple hearth regeneration systems could restore the carbon adsorption capacity equally well.

Furnace Life

After almost 18 months of installation and operation, the interior surfaces of both rotary kilns were found seriously corroded. One of the two rotary kilns actually broke into two sections during a special regeneration of some odor control carbons on June 14, 1977. This special regeneration might have enhanced the corrosion rate by producing the sulfur oxides which might be converted to corrosive sulfuric acid fume. The corrosion was particularly

serious within the first 1.2 m (4 ft) section near the carbon feed end. The broken kiln was replaced with a similar kiln to complete the fourth regeneration cycle.

In comparison with the multiple hearth furnace used in a previous carbon adsorption study under similar operating conditions, the useable life for the rotary kiln furnace was much shorter than the actual 12 years of functional period for the multiple hearth furnace pilot system[3].

PERFORMANCE OF AIR POLLUTION CONTROL SYSTEM

During the second carbon regeneration cycle, the emissions from the afterburner stack of the rotary kin regeneration system were tested by the South Coast Air Quality Management District (SCAQMD). The flue gases at the outlet of the afterburner were tested for flow rate, temperature, particulate matter, carbon monoxide, carbon dioxide, oxygen, odor number and oxides of sulfur.

Gas flow measurements were made with a standard pitot tube and a magnetic draft gauge. The gas temperature was measured with chromel-alumel thermocouple and a portable potentiometer. The test for particulate matter was performed using a wet impingement method. Samples for the determination of oxides of sulfur were collected by an impinger train containing 5 percent NaOH. During the test period, gas samples were also collected and analyzed with a conventional Orsat analyzer for CO_2 and tested with a Teledyne oxygen analyzer for O_2. A gas chromatograph-combustion-infrared technique was used to determine the concentration of carbon monoxide.

Table 7 presents a summary of the emission data from the afterburner stack. During the entire second regeneration, odors and smoke were not detected. As indicated by the data, the measured emissions were within the allowable limits. However, it should be mentioned that because of the configuration of the afterburner stack, an indeterminate amount of ambient air invariably provided natural dilution of the emissions from the regeneration system. Thus, the measured emissions reported in Table 7 represented the diluted concentration of the air pollutants. If an appropriate air dilution factor were applied, the actual emission concentration would be higher. Consequently, it is most likely that without the dilution effect the actual particulate emissions would exceed the allowable limits.

The above concern has caused the SCAQMD to deny the Sanitation Districts' permit application for further operation of the rotary kiln pilot plant. It has been required to modify the air pollution control system of the rotary kiln furnace to meet the control limits of particulates, carbon monoxides and oxides of sulfur without clean air dilution. The SCAQMD has suggested that a venturi-scrubber, a high efficiency afterburner, and a sulfur dioxide scrubber be added to minimize the above pollutants, respectively.

Table 8 shows the results of the evaluations of the air pollution control system of the multiple hearth furnace. The data indicated that all emission

TABLE 7

SUMMARY OF EMISSIONS FROM THE EXTERNALLY-FIRED ROTARY KILN CARBON REGENERATION SYSTEM

Parameter	SCAQMD Emission Limit	Measured Emissions From Afterburner Stack
1. Particulate Matter		
Concentration, grain/SCF	0.196	0.185
Emission Rate, lb/hr	0.990	0.700
2. Oxides of Sulfur, (SO_2)		
Concentration, ppm by volume		67.00
Emission Rate, lb/hr		0.36
3. Carbon Monoxide (CO)	2000.00	530.00
4. Odor		
Odor Unit/SCF		NONE
5. Gas Flow		
Temp., °F		415.00
Rate, SCFM		530.00

NOTES: 1. SCAQMD = South Coast Air Quality Management District

2. lb/hr X 0.454 = Kg/hr; (°F - 32) X $\frac{5}{9}$ = °C; SCFM X 0.472 = l/sec; grain/SCF X 2.29 = g/cu m

TABLE 8

SUMMARY OF EMISSIONS FROM THE MULTIPLE HEARTH CARBON REGENERATION PILOT SYSTEM (Ref. 3)

Parameter	APCD Emission Limit	Measured Emissions (Test Series I)			Measured Emissions (Test Series II)		
		Baghouse		After-Burner Outlet	Baghouse		After-Burner Outlet
		Inlet	Outlet		Inlet	Outlet	
1. Particulate Matter							
Concentration, grains/SCF	0.20	0.987	0.298	0.046	1.82	0.47	0.075
Emission rate, lb/hr	1.00	0.890	0.266	0.09	2.17	0.80	0.24
2. Oxides of Nitrogen, (NO_x)							
Concentration, ppm dry	225	94		166	40	--	180
Emission rate, lb/hr				0.48	0.028	--	0.40
3. Oxides of sulfur (SO_2)							
Concentration, ppm SO_2	0.2%			217	nil	nil	149
Emission rate, lb/hr				0.88	--	--	0.57
4. Hydrocarbons							
Concentration, ppm C		3900		660	740	561	nil
Emission rate, lb/hr C		0.88		0.50	0.20	0.21	--
5. Carbon Monoxide (CO)							
Concentration, % Volume dry		0.56		0.20	1.36	0.86	0.11
6. Odor							
Odor unit/SCF		20,000		10	20,000		20
7. Gas Flow							
Temperature, °F		354	140	1000	352	159	1148
SCFM		104	104	392	139	198	376

NOTES: 1. APCD = Air Pollution Control District (Los Angeles County, California)

2. lb/hr X 0.454 = Kg/hr; (°F - 32) X $\frac{5}{9}$ = °C; SCFM X 0.472 = l/sec; grain/SCF X 2.29 = g/cu m

parameters, such as particulate matter, oxides of nitrogen, oxides of sulfur, hydrocarbon, and odor number, were all in full compliance with the local air pollution control requirements.

An 182 kg/hr (400 lb/hr) plant-scale multiple hearth carbon regeneration system has been in operation at the Sanitation Districts' Pomona Water Reclamation Plant, Pomona, California, since early 1977[10]. This furnace is provided with an adequate air pollution control system which consists of only a venturi wet scrubber and an afterburner. The satisfactory results form this air pollution control system seem to indicate that the same type of system may be able to provide an adequate control of the emissions from the rotary kiln regeneration system. The combination of cyclone and baghouse used in the pilot-scale multiple hearth regeneration system can reliably be replaced by the venturi wet scrubber unit[3].

COST ESTIMATE

Criteria for Cost Estimates

An economic analysis has been prepared to compare the carbon regeneration costs between a multiple hearth furnace system and an externally-fired rotary kiln furnace system. The furnace capacity used for the cost comparison analysis is 182 kg/hr (400 lb/hr). This capacity is based on the requirement of a typical 0.44 cu m/sec (10 MGD) carbon adsorption plant with a carbon exhaustion rate of 75 g/cu m (650 lb/MG). Table 9 shows a summary of the various assumptions used for the preparation of the cost estimates.

Itemized Cost Estimates

The cost estimates for the furnace systems have been divided into two subcategories; namely, capital cost, and operation and maintenance costs. The equipment cost consists of carbon dewatering and feed system, furnace system (including steam generator), and air pollution control system (including an afterburner and a venturi wet scrubber). Additionally, the capital cost also includes the initial engineering cost (10 percent of equipment cost), equipment shipping and installation cost (125 percent of equipment cost), and contingency (20 percent of equipment cost). The operation and maintenance costs include the utilities, operating and maintenance labor, carbon makeup, maintenance materials, and rotary tube replacement. A summary of these various cost items is shown in Table 10.

Cost Comparison

As indicated in Table 10, the capital cost (with a 20 year amortization at an interest rate of 10 percent) for a multiple hearth furnace is about 7.52 cents per kilogram of carbon regenerated (3.42 cents/lb of carbon), while it is about 4.20 cents per kilogram of carbon regenerted (1.91 cents/lb of carbon) for an externally-fired rotary kiln furnace with an equivalent regeneration capacity. The major difference (more than 44 percent) in the capital cost estimates is basically associated with the substantial difference in the

TABLE 9

CRITERIA AND UNIT COSTS FOR CARBON REGENERATION COST ANALYSIS

Criteria		
1.	Plant flow, MGD (cu m/sec)	10 (0.44)
2.	Carbon dosage, lb/MG (g/cu m)	650 (75)
3.	Carbon feed rate, lb/hr (Kg/hr)	400 (182)
4.	Steam consumption rate, Kg/Kg of carbon	
	Multiple hearth	0.6
	Rotary kiln	0.3
5.	Fuel consumption rate (including furnace and afterburner), BTU/lb of carbon (kJ/kg of carbon)	
	Multiple hearth	4,000 (9,3000)
	Rotary kiln	8,000 (18,6000)
6.	Power consumption rate, KWH/lb of carbon	0.02
7.	Carbon loss, %	7
8.	Labor, man-hr/lb of carbon (man-hr/kg of carbon)	
	Multiple hearth	0.00615 (0.0135)
	Rotary kiln	0.00492 (0.0108)
Unit Costs		
1.	Carbon, cents/lb (cents/Kg)	60 (132)
2.	Fuel, cents/therm	14
3.	Power, cents/KWH	4
4.	Labor, $/man-hr	10

Other Assumptions

1. Maintenance materials: 5% of equipment cost/year
2. Shipping and installation: 125% of equipment cost.
3. Initial engineering: 10% of equipment cost.
4. Contingency: 20% of equipment cost.
5. Amortization: 20 years at 10% interest rate.
6. All furnace systems are constructed on sites.
7. Rotary tube is replaced once every three years.

TABLE 10

SUMMARY OF CARBON REGENERATION COST ESTIMATES

Cost Item	Multiple Hearth		Rotary Kiln	
	1000 of $	cents/lb carbon	1000 of $	cents/lb carbon
Capital:				
1. Equipment				
a. Carbon dewatering and feed system	20		20	
b. Furnace system	236		116	
c. Air pollution control system	15		15	
2. Shipping and Installation	339		189	
3. Engineering	27.1		15.1	
4. Contingency	54.2		30.2	
5. Total Capital Cost	691.3		385.3	
6. Capital Amortization		3.42		1.91
Operation and Maintenance				
1. Utilities				
a. Steam		0.11		0.05
b. Power		0.08		0.08
c. Fuel		0.56		1.12
2. Labor		6.15		4.92
3. Carbon make-up		4.20		4.20
4. Maintenance material		0.57		0.32
5. Rotary tube replacement		--		0.68
Grand Total for Process Cost:		15.09		13.28

NOTE: cents/lb carbon X 2.2 = cents/Kg carbon

costs for furnace equipment. The rotary kiln is a simpler and cheaper furnace system than the multiple hearth furnace system.

Although the rotary kiln furnace is simpler in design and thus less in maintenance requirement, yet the life of the rotary tube is rather short. It is assumed that a replacement of the rotary tube is necessary for every three years of operation at a cost of 40,000 dollars per replacement. On the other hand, the multiple hearth furnace has a much longer useable life span which is accomplished by a rather costly routine maintenance work. As a result of these differences in furnace life span and maintenance requirement, the total operation and maintenance costs for the multiple hearth (25.67 cents/kg of carbon or 11.67 cents/lb of carbon) and the rotary kiln (25.01 cents/kg of carbon or 11.37 cents/lb of carbon) furnace systems become very close to each other, with only 2.6 percent difference.

Since the capital costs of the furnace systems represent only small fractions of the total process costs (22.6 percent in multiple hearth system and 14.4 percent in rotary kiln system), the difference between the total process costs of the two furnace systems is not greatly affected by the difference in their capital costs. The overall difference in the process cost estimates is only about 12 percent, with the rotary kiln furnace system slightly cheaper than the multiple hearth furnace system.

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